NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

TECHNICAL MEMORANDUM 1249

SUSCEPTIBILITY TO WELDING CRACKING, WELDING SENSITIVITY, SUSCEPTIBILITY TO WELDING SEAM CRACKING, AND TEST METHODS FOR THESE FAILURES

By K. L. Zeyen

Translation of "Schweissrissigkeit, Schweissempfindlichkeit, Schweissnahtrissigkeit und Prüfverfahren für diese Fehlererscheinungen." ZWB Luftfahrtforschung Band 20, Lfg. 8/9, October 16, 1943

Washington
June 1949

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SUSCEPTIBILITY TO WELDING CRACKING, WELDING SENSITIVITY, SUSCEPTIBILITY TO WELDING SEAM CRACKING, AND TEST METHODS FOR THESE FAILURES*

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In the years after the First World War a very rapid development, which even today has by no means come to an end, took place in the field of welding; here also, as in most technical innovations, failures made their appearance. Thereupon comprehensive investigations were undertaken by steel manufacturers and consumers with cooperation of the authorities. In most cases the reasons for failure could be determined and eliminated and further occurrences avoided by the use of new test methods.

OUTLINE

A. CHARACTERISTIC DIFFERENCES OF VARIOUS FAILURES

During the last years, mostly three types of failure were observed in the fusion welding of steels; their forms of appearance are as

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*"Schweissrissigkeit, Schweissempfindlichkeit, Schweissnahtrissigkeit und Prüfverfahren für diese Fehlererscheinungen." Zentrale für wissenschaftliches Berichtswesen der Luftfahrtforschung des Generalluftzeugmeisters (ZWB) Berlin-Adlershof, Luftfahrtforschung Band 20, Lfg. 8/9, October 16, 1943, pp. 231-241.

different as the reasons causing them. Susceptibility to welding cracking, like welding sensitivity, results in the forming of cracks in the welded base metal near the welding seams. In the first case the cracks appear only in gas welding of thin steels of higher strength. They originate at high temperatures during the welding. Welding sensitivity, on the other hand, appears in general only in arc welding, particularly of thick dimensions of material and also of soft steels. The cracks occurring here in the welded base metal originate either by the cooling off after the welding, or after the welding has been terminated, or else only later by the stresses on the welding pieces occurring in operation. The causes for the susceptibility to welding cracking, as well as for the welding sensitivity, lie mainly in the welded base metal. On the other hand, in most cases of susceptibility to welding seam cracking, which like welding sensitivity is observed almost exclusively in arc welding, the weld material is responsible for the cracks originating here in the welding seams.

B. SUSCEPTIBILITY TO WELDING CRACKING

The designation "susceptibility to welding cracking" is now universally accepted for the appearance of cracks in the welded base metal in gas welding of thin steels of higher strength; formerly other designations, such as "welding" or "heat sensitivity," were used as well. The inclination toward susceptibility to welding cracking increases, in general, with decreasing thickness of the material, with increasing strength of the material, and with increasing complexity of the welded connections (and therewith with the high degree of the originating welding stresses). For soft unalloyed steel with carbon content up to about 0.2 percent and with strength to about 42 kilograms per millimeter^2, susceptibility to welding cracking has not been observed so far. However, the changing from soft unalloyed steels to steels of higher strength that took place in various branches of industry, for instance in aircraft construction in Germany as well as abroad around the year 1928, at first caused frequent appearances of susceptibility to welding cracking, in particular in fillet weldings where the stress on the material is generally higher than in butt weldings. Test methods of a new type had to be developed for finding and eliminating the causes; with these new test methods it was possible to induce the same welding stresses that occur in difficult operational weldings.

Figure 1 shows a special experiment for the development of such a test method. The photograph at the left shows a gas welding where a metal sheet of 1.2-millimeter thickness, the fillet seams of which were arranged so that high welding stresses were caused, was welded on to another one of the same thickness. The reverses of such weldings (presented at the right) show that for an unalloyed steel of about 0.35 percent C the material cracks considerably in the places denoted by arrows, whereas a material of the same strength which had a low content of carbon and was alloyed with silicon and manganese remained free from cracks.

Various new test methods for the susceptibility to welding cracking were developed in aircraft construction where steels not susceptible to welding cracking are of special importance. Figure 2 shows the so-called fusion or penetration tests, at the left the simple or Fokker test, at the right the zigzag or Focke-Wulf test. For the first one the material, starting at the center of a sheet-metal edge, is fused to a piece of sheet metal of 100 × 100 millimeters^2 size and 1- to 2.5-millimeter thickness up to the center of the test piece by means of a burner, but is not fused through. Simple as this test looks, it results in one of the sharpest material stresses imaginable. For the zigzag test where the strain on the material is somewhat less high, the fusing which begins at the sheet corners is led not quite up to the center of the test piece and ends at the center of the sheet edges. The effect of both fusing tests may be modified by using the burner not only for fusion of the sheets but simultaneously for applying beads with auxiliary wire. The numerical evaluation in the fusion or penetration tests is made with and without use of auxiliary wire by measuring the length of the cracks which have originated beside or underneath the smelts or applications.

Figure 3 shows a further test for susceptibility to welding cracking developed in aircraft construction. This so-called cross welding test is performed as follows: two metal sheets of 50 × 200 millimeters^2 size and, in general, 1- to 2.5-millimeter thickness are connected by encircling fillet seams that immediately join each other (representation at the left of fig. 3). The specimens must therefore be turned three times during the welding. After the test pieces have cooled off, the length of the cracks appearing in the material beside or underneath the fillet seams is measured; another measurement of the crack lengths is taken after bending the free flanges of the test specimens in the screw vice 90°, which for the most part causes the cracks already formed in welding to grow still wider. The bending of the free flanges of the specimens should be done so that the fillet seams lie within the 90° angle as shown in figure 3, at the right.

One objection to the tests represented in figures 2 and 3 is that they are too severe because they also characterize as susceptible to welding cracking materials which are successfully welded in practice.

J. Müller (reference 1) developed the clamp welding test; the apparatus for this test and a welded test specimen are shown in figure 4. Two identical test specimens of 50 × 75 millimeters^2 size and thicknesses up to 2.5 millimeters are firmly clamped in the apparatus so that a gap equalling the sheet thickness remains between them; this gap is welded autogeneously with auxiliary wire so that the two sheet-metal pieces are afterwards joined by butt welding. The specimens are supposed to cool off while clamped in; then the welding seam is broken from the butt weldment. The lengths of the surface portions of the fractures, where oxidized spots due to crack formations in welding have appeared, are measured and the ratio to the entire welding seam length is determined; the measure for the susceptibility to welding cracking therefrom results in percent. In a more severe test used recently a test sheet of a thickness up to 2.5 millimeters is butt-welded to a considerably thicker one (in general 5 millimeters)(reference 2). The test values obtained in the clamp welding test are in good agreement with welding experiences in practice. The test was introduced in the German aircraft factories by order of the Ministry for Aeronautics of February 4, 1936.

The tests for susceptibility to welding cracking represented in figures 1 to 4 concur in showing a decreasing inclination toward welding cracking with increasing thickness of the material. For gas welding the material is the more endangered the smaller the thickness used.

The newly developed test methods made it possible to determine the causes of susceptibility to welding cracking so that this failure could be remedied. For once the sources of failure, such as conditions of welding technique or construction (faulty shopwork and faulty construction), did not lie in the base metal. It is to be noted that the degree of purity of the acetylene gas used which is different for cylinder gas and generated acetylene proved to be of no influence (reference 3). The main source of failure was found in the welded base metal. Table 1 (reference 4) gives a compilation of test values (from various tests) for susceptibility to welding cracking in aircraft construction. Here it is sufficient to compare the values for the clamp welding test which most resemble the conditions in welding practice. It may be mentioned that the rest of the tests for susceptibility to welding cracking, which in themselves are too severe, were not appropriate for acceptance tests but rendered very valuable service in the development of steels with particularly high insusceptibility to welding cracking. The values of table 1 show that for unalloyed steels - provided that they are manufactured the same way - the carbon content determines whether or not a steel is susceptible to welding cracking. A steel with only 0.11 percent C was as free from welding cracks when welded as special higher strength steels of low carbon content alloyed with silicon and manganese. Unalloyed steels, on the other hand, with 0.3 and 0.68 percent C of the same strength as the last mentioned special steels, showed a high degree of susceptibility to welding cracking which increased with higher carbon content. For chrome-molybdenum steel there resulted, as shown in table 2 (reference 4), at first a predominant effect of the fusion method. Normally manufactured electrosteel remained free from cracks in the clamp welding test, whereas normally manufactured SM-steel with the same analysis showed degrees of susceptibility to welding cracking of 20 to 28 percent. In the same fusion method there appeared also a considerable influence of a special fusion treatment which essentially consists of application of an intensified deoxidation which leads to fine-grained steel. The reproduced, specially treated SM-fusion showed less welding cracking in the clamp welding test than the normally manufactured SM-fusions, in spite of a very high carbon content which is unfavorable for susceptibility to welding cracking. Even for electrosteel an improvement could be obtained by metallurgic measures, in the melting procedure. In order to recognize this, however, test values of the clamp welding test (table 2), which indicated freedom from cracking in all cases for electrosteel, must no longer be considered. But the test values of the other tests for susceptibility to welding cracking, which are per se too severe, demonstrate that by special measures chrome-molybdenum steel manufactured in the electric furnace also can be still further improved with respect to insusceptibility to welding cracking. It should be mentioned here in addition that for unalloyed steels, also, a considerable influence of the melting process and of the melting treatment in the furnace was found to exist inasmuch as steels of higher carbon content which like normally manufactured SM-steels are always highly susceptible to welding cracking, showed this phenomenon much less when manufactured in the electric furnace, both with and without special melting treatment (reference 5).

The numerous investigations which were made at different places and gave valuable assistance in clarifying the causes of susceptibility to welding cracking shall not be more closely discussed here. Aside from the permissible degree of contents of alloying elements like carbon and chrome, or impurities like phosphorous and sulphur, and from the influence of the type of melting furnace and of the melting treatment, these investigations dealt with the influence of a heat treatment and therewith of the structure of the steel, the influence of the direction of rolling, and the type of additional material used. Universally the important observation was made that the welding hardness, that is, the hardness of the zones beside the welding seam affected by the welding heat (which is highly dependent on the composition of the steel), has no connection with the steel's inclination for susceptibility to welding cracking. Steel manufacturers and consumers immediately made practical use of the results of the performed tests. Since the order of the Ministry for Aviation of January 1, 1936, the manufacture of chrome-molybdenum steel for welding in aircraft construction was permissible in Germany only in the electric furnace with fixed upper limiting values of phosphorous and sulphur, until this steel had to be replaced by steels less rich in high priority material. Of interest in this connection are data obtained from the USA (reference 6) for 1941, according to which the American steel used in aircraft construction, SAE X4130 (which corresponds in composition to a great extent to the steel used in Germany), was originally manufactured only in the electric furnace but recently has been smelted also as SM-steel though only with small casehardening weights. An unobjectionable deoxidation, evident by a small grain size, is indicated as preliminary condition for good weldability or rather for insusceptibility to welding cracking. Thus American experiences agree completely with German ones.

Figure 5 shows that for chrome-molybdenum steel welding cracks run along the grain boundaries (intercrystalline). The same holds true for other steels with inclination toward susceptibility to welding cracking, as well as for unalloyed steels of higher strength. Until the year 1941, the range between 600° and 1000° C had been determined as the formation temperature of welding cracks. A. Antonioli (reference 7), however, proved in 1942 that most of the numerical values given so far in the literature must be regarded as too low, due to inadequate measuring apparatus. With the aid of a newly developed physical measuring method, Antonioli determined the temperature range of crack formation for susceptibility to welding cracking of chrome-molybdenum steel to be 1350° to 1000° C, with a maximum frequency at 1275° (fig. 6).

The problem of susceptibility to welding cracking in gas welding of thin steels of higher strength may be assumed to be solved today. It is first of all a question of material. Under the influence of welding stresses at red heat in material which is susceptible to welding cracking, cracks which run intercrystallinely appear beside gas welded seams. Decisive in the manufacture of steels insusceptible to welding cracking is, first, their chemical composition and, second, the method of manufacturing; an intensified deoxidation leading to fine-grained steel proved to be particularly effectual.

The type of susceptibility to welding cracking which can occur in gas welding is not observed in arc welding. One of the causes is the different type of calorific effect of the electric arc as compared with the flame of the burner; another is the fact that in arc welding the thickness of the material is generally greater than in gas welding. In gas welding, the thinner the material, the greater is its susceptibility to welding cracking.

C. WELDING SENSITIVITY

In arc welding, particularly of medium and large thicknesses of material, failures may occur which appear similar to susceptibility to welding cracking in gas welding of thin dimensions; however, the causes are different. When steels are arc-welded, which because of their content of alloying elements have an inclination toward strong rehardening beside the welding seam, cracks appear sometimes beside or in welding seams before the welded parts are subjected to stresses, even though construction and metal arc weld were suitable. The cracks run through the rehardened zone parallel or perpendicular to the welding seam, not along the grain boundaries as in susceptibility to welding cracking but through the crystal grains (intercrystalline) as shown in figure 7. Either the cracks occur only after the weld has finished cooling off and show metallic-bright fractures, or they originate by the cooling off after the welding and are then characterized by tempering colors. The formation temperature, however, is always essentially lower than in susceptibility to welding cracking. Such cracks are best denoted as cracks due to weld embrittlement or rehardening; they may be explained by the fact that the rehardened zone is strongly infringed upon in its deformability and will crack under the influence of the welding and contraction strains, usually starting from penetration notches. A remedy will be the selection of a less hardenable material or sometimes also the use of welding rods of great flexibility, for instance austenitic ones (reference 8) which due to the high deformability of the welding material will be able to absorb an essential part of the contraction strains and to deflect them from the rehardened zone. Operational experiences seem to show that, for steels of higher strength sensitive to hardening, thin sections (for instance, metal sheets below about 5-millimeter thickness) prove to be more sensitive with respect to the formation of cracks due to weld embrittlement than thicker sections; to such an extent a certain analogy would exist with the welding cracking which occurs only in gas welding. In accordance with existing experiences, the effect of heat should be kept at a minimum for thinner steels sensitive to hardening by the electric arc, so as to keep the resulting welding stresses low. This aim can be obtained for instance by selection of small-sized electrodes and amperages and by use of electrodes which, in welding, develop as little heat as possible (bare, core, or thinly coated electrodes). However, for thick material and small heat supply, a very strong rehardening with high local tension points would occur due to the rapid escape of the heat so that here, in contrast to thin materials, a large heat supply would be advisable in order to avoid cracks due to weld embrittlement. This heat supply can be obtained by preheating, use of larger electrodes, higher amperages, and thickly coated electrodes.

A steel is called welding sensitive which strongly rehardens by the welding heat and shows an inclination toward cracking due to welding embrittlement, even without operational stress, because of the welding and contraction strains. More accurately, it should be denoted as little suited for welding or as suited for welding only under special conditions. H. Buchholtz and P. Bettzieche (reference 9) designate welding sensitivity as the inclination of a material to undergo, in arc welding, particularly in deposit welding, changes of properties to such an extent that the strains occurring during the welding are no longer absorbed by deformation but lead to tension cracks. Under otherwise equal conditions, steel shows the more sensitivity the more it is inclined to quench hardening, due to its composition and conditions of production. E. H. Schulz and W. Bischof (reference 10) define welding sensitivity in general as the inclination of a material toward formation of cracks in welding.

The concept "welding sensitivity" must be defined more broadly however. So far, the suitability of a steel for the purposes of fusion welding was tested only by investigating rather small welded specimens of 10- to 12-millimeter thickness. In such tests the originating welding stresses are small, especially when the specimens are welded without clamping, as is mostly done, and can freely give way to shrinkage. The weldability of the material was proved, if the proof testing resulted in the obtaining of certain mechanical properties. Recently it was shown, however, that the basic suitability of a steel for fusion welding, proved by such a test, does not yet guarantee a faultless welding for practical operation; this holds true particularly for a steel of higher strength under unfavorable conditions, as in rigid clamping of the parts or for very large or very different thicknesses of material. Furthermore, it was found that even with seemingly faultless welding one could not be sure that under operational stress the weldings would not show after some time the phenomena of fracture.

In the well-known cases of damage on welded bridges, fractures without deformation occurred in St 52 over 30 millimeters thick. The importance of these failures ought not to be overrated, for these are single cases among thousands which give full satisfaction (reference 11).

A great many investigations have been made to determine the reasons for these and similar cases of damage; those by G. Bierett (reference 12) and O. Graf (reference 13) were especially thorough. The German Railways assumed at first, certainly not without some reason, that the appearance of fractures without deformation in weldings on thick cross sections of St 52 is connected with the hardenability in welding caused by hardening alloying elements. Thus they prescribed limits of analysis in 1937; after war broke out, these were changed again to the form given below:

LIMITING VALUES IN THE ANALYSIS FOR WELDABLE STRUCTURAL STEEL St 52 SET UP BY THE GERMAN RAILWAYS ON DECEMBER 28, 1939

C maximum 0.2 percent	With additional:
Si maximum 0.6 percent	Up to 0.2 percent Si
Mn maximum 1.2 percent	Or 0.4 percent Mn
P maximum 0.06 percent	Other alloying elements
S maximum 0.06 percent	such as Cr, Mo, and Cu
P and S maximum 0.1 percent together	are not permissible.

Numerous investigations show, however, that other factors like the chemical composition influence to a much higher degree the behavior of a steel in tests from which conclusions are to be drawn as to the multiaxial state of stress which develops in welding of thick profiles and its effect on the structure. Such factors of influence are: the construction, type of weld, smelting, and the heat treatment condition of the steel. Figure 8 shows an example in polished cross cuts of the rehardening observed by E. H. Schulz (reference 14) in the welding of a front cross section and of an elevation cross section; such profiles, together with a number of others, are used for weldings in bridge construction (reference 15). The hardening strips in these two profiles are of a very different formation. In the first case they run separated from each other at both sides of a still uninfluenced zone of material which can assist in stress reduction, like the gap in the base of the welded connection. In the latter case, however, there exist two hardening strips running into one another which separate the weld material from the uninfluenced base material and hinder a reduction of stress due to their high yield point.

The German Railways introduced the free-bend-test or bead-bending-test according to figure 9; these are test methods which indicate the ability of a steel material to absorb the multiaxial state of stress (which appears in the welding of thick profiles under the influence of the welding stresses and, later, the operational stress) in such a manner that no fractures occur without deformation (reference 16). Certain minimum bend angles, depending on the type of steel, have to be reached; furthermore it is required that the specimen must show a clear evidence of deformation in fracturing and must not break without deformation. For St 37 a minimum bend angle of 50° is required for 50-millimeter thickness, 40°, for 40-millimeter thickness, and 50° for 30-millimeter thickness for the breaking of the specimen, whereas for St 52 numerical values have not yet been determined. The free-bend test does not correspond to an ideal exactly defined test method; so far it could not be proved that there are relations between its test values and the practical quality of a steel in a welded structure. Furthermore, there is no agreement on the problem of whether it would not be more to the purpose to determine the bend angle at the first crack in the base metal instead of the bend angle at the breaking of the test specimen (reference 17). However, the free-bend test makes it possible to induce the same fractures in steels without deformation as have occurred in welded bridges of St 52 having thick material; it has also led to the development of types of St 52 and of soft steels which, due to measures in melting technique or heat treatment, show good deformation when fractured.

Figure 10, according to H. Buchholtz (reference 18), shows at the top a distinct deformation fracture, at the bottom a typical rupturing fracture. For the first, the fracture looks mat-fibrous without crystalline surfaces; for the latter, predominantly crystalline, running on the crystal boundaries without any evidence of deformation. In a mixed fracture, as represented in figure 10, center, a crystalline course of fracture is stopped by surfaces of deformation. The German Railways classify this type of fracture still as deformation fracture.

The bending angles found in the free-bend test depend on numerous influencing factors which have no bearing on the welded base metal: the thickness of the specimen, the position of the top weld, the type and diameter of the welding rod used, the welding and testing temperature, the possible application of a supplementary heat treatment, and the test place (reference 19). Only after all these factors had been exactly determined was it possible to perform investigations aiming at examining the influence of the base metal on the size of the attained bend angle.

Experiments have been made on a large scale in many places in order to replace the free-bend test, which requires great quantities of material and large test apparatus, by a simpler test for determining the welding sensitivity. However, these experiments have so far not met with full success. At some test places, certain relations were observed between the test values of the free-bend test specimen and those of the sharp-notch-impact test specimen of unwelded material, the quench hardness of unwelded specimens, the austenite grain size of the steel, the magnitude of the transformation range $A_{C_1} - A_{R_1}$, and the test values of still other methods. However, these observations will certainly have to be checked thoroughly at other places and on other steels before a law can be established for them. H. Hauttmann (reference 20) suggested as substitute for the free-bend test the groove-compression-bend test where, by pressing in of a longitudinal groove with additional cross notch, an increase in hardness and a state of internal stress is reached in the transition zone of the test specimen, as in welding. (The specimen is artificially aged before the test.) The test results are said to be about in agreement with those of the free-bend test: however, the groove-compression-bend test does not represent a simplification since the pressing in of the groove requires a 500-ton press which probably only few plants possess.

In the USA also, numerous test methods for weldability or welding sensitivity have been developed which shall not be discussed here. Details were given in a report written by the author of this article about an American treatise (reference 21). It is improbable that one of these test methods, all performed on rather thin metal sheets, would provide a correlation between the values of the free-bend test on the one hand and the experiences in practice on the other hand, since in such tests the effect of large thickness of material cannot be obtained; it is this effect which in welding leads in general to multiaxial states of stress and the appearance of fractures without deformation. The same is valid for several test methods developed in England. Figure 11 represents the so-called IMS-test (reference 22) where pieces of sheet metal butted together are connected by fillet seams with a third piece put over them; rigid clamping is used. Polished cross cuts made from them are examined as to cracks and subdivided into different grades. The Swinden-Reeve test (reference 23) according to figure 12 is similar. Here also fillet seams are welded under rigid clamping; by bracing the test sheets on a 50-millimeter-thick base plate a very rapid escape of the heat in welding is obtained and therewith a high degree of hardening in hardenable steels. Figure 13 represents four different types of cracks as they can be found in cross cuts from Swinden-Reeve test specimens.

In the numerous tests made for clarification of the free-bend test, it was observed that for specimens of 50-millimeter thickness soft steel may show fractures without deformation just as St 37, depending on its fusion and heat treatment. Thus the free-bend test may strongly influence the deformability even of soft steels, not less than in operational welding of thick profiles. In this connection, the publication of H. Busch and W. Reulecke (reference 24) and the exchange of notes with G. Bierett (reference 25) about the probable causes of fracture in a Belgian bridge welded from soft semikilled Thomas steel should be mentioned. Busch and Reulecke point out that for the concept of welding sensitivity a sharp distinction ought to be made between (a) the flexibility of a welded material during the testing, as evidenced for instance by the testing of a welded material in a multiaxial state of stress, as in the free-bend test, (b) the appearance of cracks during the welding; so far H. Buchholtz and P. Bettzieche (reference 9), as well as E. H. Schulz and W. Bischof (reference 10), wanted the designation "welding sensitivity" applied only to this phenomenon.

They also point out that it is not permissible to connect the various properties of material characterized under (a) and (b) by a more comprehensive expression like "suitability for welding" or "weldability." The result might be, as in the case of the Belgian bridge, that the soft Thomas steel used would have to be designated as insensitive to welding according to (b) while it would have failed when tested in the multiaxial state of stress according to (a). G. Bierett (reference 25) on the other hand stresses that the concept "welding sensitivity" ought to be understood as a relative concept which gives evidence as to whether a material undergoes more or less drastic critical changes of its properties that are important for the practical application. With this explanation the free-bend test can be easily classified as one of the means for determining the welding sensitivity.

K. Brückner (reference 26) gave a compilation of the perceptions gained by the free-bend test with respect to materials and dimensions for welded structures. O. Kommerell (reference 27) could state, in 1942, that the welding of bridges with covered trusses of St 52 certainly will be fully resumed after the war since the reverses suffered at one time have been overcome today.

The problem of welding sensitivity is of less importance for medium thicknesses of material (somewhere between 6 and 20 millimeters) as already proved by the fact that in vehicle and ship construction very large quantities of St 52 have been welded without failures on a larger scale. The failures in bridge construction occurred only in the welding of large thicknesses of material which may lead to very high welding stresses. Anyway, special care should be taken, even in welding of smaller thicknesses of steels of higher strength, that by means of good construction and the type of welding the welding stresses are kept low.

According to the given data, no uniform interpretation exists so far as to how broadly to define the concept "welding sensitivity." Furthermore, a suitable test which could be generally used for judging the welding sensitivity of a steel is still lacking, since the latter depends too much on the cross-sectional dimensions of the material. Foreign publications express the same opinion (reference 28).

H. Buchholtz (reference 18) draws the conclusion that so far none of the known test methods has proved its practical validity for evaluating the weldability of a steel. Thus for the present, several test methods for welding sensitivity, selected according to the type of welding, would have to be applied along with the familiar characteristic values of a steel, as chemical composition and properties of strength.

D. SUSCEPTIBILITY TO WELDING SEAM CRACKING

In susceptibility to welding cracking and in welding sensitivity, one deals with cracks in the material beside welding seams; the phenomenon of longitudinal or cross cracks, forming during the cooling off in the welding seams and sometimes continuing into the base metal, is denoted as susceptibility to welding seam cracking. Susceptibility to welding seam cracking, where cross cracks appear less frequently than longitudinal cracks, occurs almost solely in arc welding, particularly of steels of higher strength and for the most part only where thickly coated electrodes are used. C. Stieler (reference 29) has treated this phenomenon thoroughly. His explanation for the fact that ordinarily fillet seams and only rarely butt seams are subject to it is that fillet seams are practically always welded in clamped condition and that the connection becomes particularly rigid by a bilateral fillet seam. A shrinking of the second seam is not possible; on the contrary, it is stretched due to the shrinking of the first seam. Bare, core, and thinly coated electrodes give in general convex fillet seams; covered electrodes, concave or perhaps plane fillet seams. The zone cooling off last is for the last case simultaneously the weakest one. Moreover, according to Stieler, for a convex fillet seam the shrinking of the entire seam cross section pulls the outer seam layer inward but shortens it, thereby subjecting it to compressive stresses, whereas for a concave fillet seam the extreme layer is subject to tensile stresses. (See fig. 14.) It may be left undecided whether Stieler's explanation is conclusive that for convex fillet seams the outer seam layer is actually subject to compressive stresses, since the seam shrinks also perpendicular to the direction indicated by the arrow in figure 14, right. G. Bierett (reference 30) traces the danger of cracking, often present in concave fillet seams, back to the course of the main stress lines due to the contraction forces, which course is undisturbed for fillet seams with approximately rectilinear boundaries. (See fig. 15, left.) However, for concave fillet seams there occurs a disturbance in the course of the lines of force near the surface with corresponding tension points. (See fig. 15, right.) The frequently observed crack source for hollow crater ends is also connected with this fact by Bierett.

Regardless of which of the two explanations mentioned is held to be more convincing, the form of the seam alone shows, at any rate, that susceptibility to welding seam cracking is observed rather frequently for covered electrodes, but seldom or never for others. Tests taken by Stieler demonstrated that there were among the covered electrodes on the market in 1937 also types which resulted in a susceptibility to cracking in fillet seams even for St 37 (cf. table 3). The values of analysis reproduced here give an indication in that the welding material of an electrode particularly susceptible to cracking contained 0.071 percent P and showed simultaneously a relatively high

C content of 0.14 percent. By introduction of sulphur into the coating of covered electrodes, the use of which did not make the material susceptible to cracking, Stieler succeeded in making those electrodes produce a weld susceptible to cracking. The author has observed in numerous tests with unalloyed or weakly alloyed electrodes that susceptibility to cracking in fillet seams often occurs when high phosphorous contents (over 0.06 percent) or high sulphur contents (over 0.05 percent) are present in the welding material. Thus it is not without reason preliminary standard DIN 1913 limits the phosphorous and sulphur contents of additional weld materials for joint weldings in the rod; one must take also into consideration the fact that the phosphorous and sulphur contents in the welding material are higher throughout than those in the welding rod; for gas welding, the explanation lies in the absorption from fuel gases, for arc welding with coated electrodes, in the absorption from the coating raw materials. In view of the present endeavors to replace Siemens-Martin steel as far as possible by Thomas steel, this fact ought not to be neglected.

However, Stieler also found in his tests a susceptibility to cracking using covered electrodes where no objection could be raised against the analysis of the welding material. Stieler did not give an explanation for that being so, but it is probable that high contents of ferric oxide in the welding material exert a harmful influence. One can also say with reasonable certainty that for covered electrodes the causes for susceptibility to welding seam cracking are to be found mostly in the coating raw materials. Therefore great caution is necessary when a coating raw material, heretofore used with excellent results and supplied from a certain source for a long time, must be taken suddenly from another supplier or from a different deposit.

According to Stieler's test results, the occurrence of susceptibility to welding seam cracking in covered electrodes depends also to a great extent on the welding conditions and is for fillet seams furthered by too high amperages and too small thickness of the first layer.

E. Helin (reference 31) made noteworthy statements, based on his own tests, about the appearance and the causes of susceptibility to welding seam cracking. According to them the electrodes must be in keeping with the steel to be welded because the composition of the two together may produce susceptibility to welding seam cracking. Due to the state of stress, fillet seams crack easier than butt seams. Susceptibility to welding seam cracking is found particularly with covered electrodes, but only rarely for steel St 37, mostly only for steels over 44 kilograms per millimeter^2 strength; semikilled steel is less susceptible than killed steel. Helin draws the conclusion that most of all the slag inclusions originating in welding, as silicic acid, advance the danger of cracking. Welding seam cracks always run in the direction of the seam, usually along the grain boundaries. If thickly coated electrodes are used, the cracks run as a rule up to the seam surface, whereas for bare, core, or thinly coated electrodes they do not reach so far; therefore they cannot be recognized from outside and are for this reason particularly dangerous.

The German Railways have developed a special fillet seam welding test for examining covered electrodes as to susceptibility to welding seam cracking; today the application of this test in the same or a similar form is made a condition in the various regulations of welding rod procedure (sound or unsound). Figure 16, top, gives this test in which metal sheets of 12-millimeter thickness made from St 00 to St 52 are joined by fillet seams. The first seam is to be welded in normal thickness; the counter seam immediately afterwards, somewhat thinner. Thereby the first seam, which is still rather hot, is stretched considerably. In electrodes very susceptible to cracking, sometimes even the first seam cracks; in less susceptible ones, only the second seam. It may be mentioned here that the German Railways had first prescribed a length of the specimen of 150 millimeters; in 1940, however, it was reduced to 120 millimeters in order to save materials. Thereby the test becomes still more severe because the second seam is laid on to a still hotter specimen. This fact explains how it was possible that several manufacturers of electrodes went through the disagreeable experience of having the German Railways, from a certain time on, denote their electrodes as susceptible to seam cracking while no objections had been made before. Tests similar to the fillet seam test of the German Railways described above have always been used by most manufacturers of electrodes. They are expedient for the further development and the control of manufacture.

Figure 16 shows three more tests for examining the susceptibility to cracking according to Stieler, which are used for alloyed covered electrodes. The test given as second is used by I. G. Ludwigshafen for testing electrodes for alloyed steels of higher strength on fillet seams on thick round steel, the test material being an accordingly alloyed steel. The two other tests (fig. 16, bottom) are used by the Krupp firm for testing austenitic electrodes. In the test represented as the next to the last, a thin layer is first welded into the root of a butt joint on a nonaustenitic or austenitic steel depending on the type of steel for which the electrode is to be used (metal sheet thickness 12 millimeters). Immediately afterwards a counter welding is made from the opposite side with an austenitic electrode which is held very firmly in order to subject the still hot test layer by the shrinking to a strong tensile stress. After having been cleaned and pickled, the test layer is examined as to cracks by means of a binocular magnifier. The test represented below which was developed by the Wilhelmshaven Navy Yard is used for the testing of austenitic electrodes for the welding of very thick cross sections of nonaustenitic steel. In this test a metal sheet St 52 of only 12-millimeter thickness is top-welded by bilateral fillet seams in immediate succession to a 50-millimeter-thick sheet metal piece of chrome-molybdenum steel having about 0.3 percent carbon; the second fillet seam is most sensitive to cracking.

E. SUMMARY

Suitable test methods for the susceptibility to welding cracking and to welding seam cracking exist at the present. By their application, an occurrence of these two types of failure may be avoided in practical operation. However, no other satisfactory test method does exist so far for the determination of welding sensitivity. Such a test method will probably never be found because the welding sensitivity depends to a high degree on the dimensions of the welded base metal, so that a test method responding well to a certain thickness of material cannot be applied for other thicknesses.

This treatise was meant to show that research work that consciously pursues its aims will not only uncover the reasons but also will indicate the remedies for failures which are almost unavoidable in all new technical developments. The closest cooperation of research and practical management is more than ever a necessity at this time.[1]

Translated by Mary L. Mahler
National Advisory Committee
for Aeronautics

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[1]The failures described here have been treated in detail in the book recently published by K. L. Zeyen and W. Lohmann, "Schweissen der Eisenwerkstoffe." Reference to this book is made for thorough orientation, particularly with regard to the extensive literature published so far.

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Table 1.- Tests for susceptibility to welding cracking made by K. L. Zeyen at the Krupp firm. Metal sheets of 1.2 mm thickness made from unalloyed steels and from low carbon steels alloyed with silicon and manganese (average values from six tests per case).

Material	Strength Kg/mm^2	Simple fusion test		Zigzag fusion test		Cross welding test		Clamp welding test susceptibility to welding cracking in percent
		Without additional rod	With additional rod	Without additional rod	With additional rod	Welded only	Welded and bent	
		Length of the cracks observed, in mm						
Unalloyed steel with 0.11 percent C	40	Flawless	Flawless	Flawless	Flawless	Flawless	Flawless	Flawless
Unalloyed steel with 0.30 percent C	55	50	45	167	119	57	2 flanges entirely, 2 flanges almost broken	51
Unalloyed steel with 0.68 percent C	78	50	50	297	160	125	All 4 flanges broken	63
Low carbon special steel alloyed with silicon and manganese (Jzett 50, j.Flw. 1263)	56	Flawless	Flawless	Flawless	Flawless	Flawless	Flawless	Flawless
Low carbon special steel alloyed with silicon and manganese (Jzett 70, j.Flw. 1265)	78	Flawless	Flawless	Flawless	Flawless	Flawless	Flawless	Flawless

Table 2.- Tests for susceptibility to welding cracking made by K. L. Zeyen at the Krupp firm. Metal sheets of 1.2 mm thickness made from chrome-molybdenum steels (average values from six tests per case).

Material								Simple fusion test		Zigzag fusion test		Cross welding test		Clamp welding test susceptibility to welding cracking in percent
Type	C %	Si %	Mn %	P %	S %	Cr %	Mo %	Without additional rod	With additional rod	Without additional rod	With additional rod	Welded only	Welded and bent	
								Length of the cracks observed, in mm						
Standard SM-steel	0.28 0.28 0.29	0.31 0.27 0.23	0.71 0.52 0.42	0.011 0.011 0.010	0.015 0.017 0.015	0.90 1.00 1.11	0.21 0.21 0.25	50 50 50	27 21 35	73 80 113	28 56 61	24 22 24	Cracks considerably widened	20 24 28
Standard electric steel	0.27 0.28 0.29	0.25 0.24 0.21	0.49 0.54 0.50	0.016 0.015 0.016	0.010 0.010 0.010	1.08 1.00 1.00	0.21 0.23 0.23	38 50 50	19 17 31	8 15 13	34 4 16	3 9 11	Cracks hardly widened	Flawless Flawless Flawless
with special fusion treatment														
SM-steel	0.33	0.32	0.70	0.011	0.015	1.08	0.21	50	17	24	Flawless	15	Cracks considerably widened	11
Electric steel	0.24	0.18	0.48	0.011	0.010	1.06	0.21	4	1	Flawless	Flawless	3	2	Flawless

Table 3.- Investigations on covered electrodes according to C. Stieler (reference 29).

Covered electrode. . . . . No.		1	2	3	4	5
Admissible for German Railway standards		E 34 z to E 52 z	E 34 z to E 52 z	E 37 z and E 52 z	E 34 z	E 34 z to E 52 z
Finding in the fillet seam test		Cracked	Flawless	Very cracked	Flawless	Flawless
Chemical composition of the welding material	C%	0.11	0.10	0.14	0.10	0.10
	Si%	0.04	0.03	0.03	0.04	0.03
	Mn%	0.55	0.50	0.50	0.43	0.32
	P%	0.046	0.046	0.071	0.035	0.033
	S%	0.029	0.029	0.035	0.030	0.039
	Cu%	0.14	0.14	0.13	0.12	0.15
	Ni%	0.05	0.04	0.05	0.05	0.04
	Cr%	0.04	0.04	0.02	0.04	0.03
	Mo%	0.23	0.22	....	....	Sp.
	N_2%	0.031	0.040	0.025	0.024	0.032
	O_2%	0.150	0.140	0.140	0.140	0.130
	H_2%	0.0004	0.0006	0.0006	0.0004	0.0011

Figure 1.

Fokker test (simple penetration or fusion test).

Focke - Wulf test (zigzag penetration or fusion test).

Figure 2.- Tests for susceptibility to welding cracking used in aircraft construction.

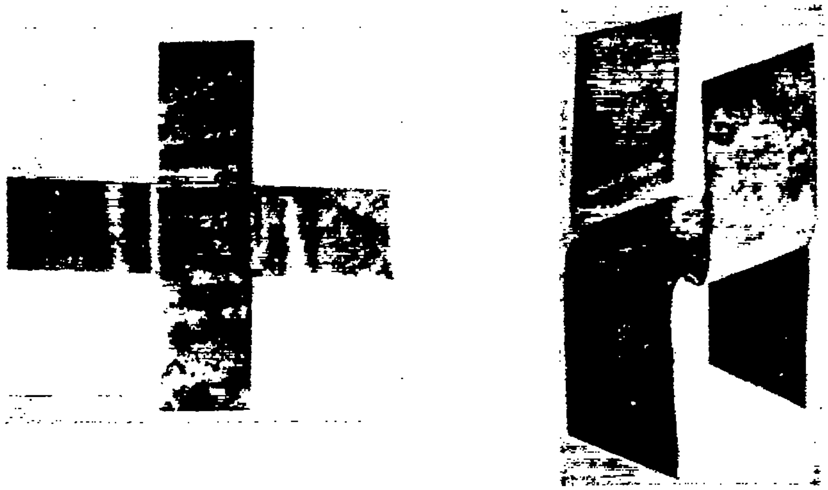


Figure 3.

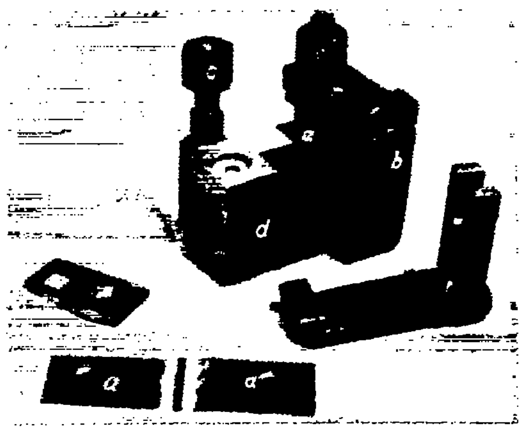


Figure 4.- Clamp welding apparatus.

(a) Welding specimen.
(b) Clamping device.
(c) Nuts.
(d) Jig.

Figure 5.- Cracks (thermal cracks) running along the grain boundaries (intercrystalline) in gas welded chrome-molybdenum steel (susceptibility to welding cracking).

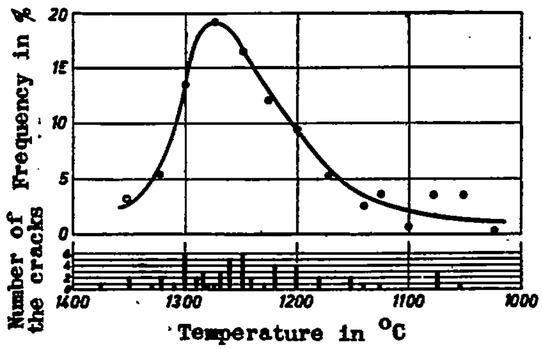
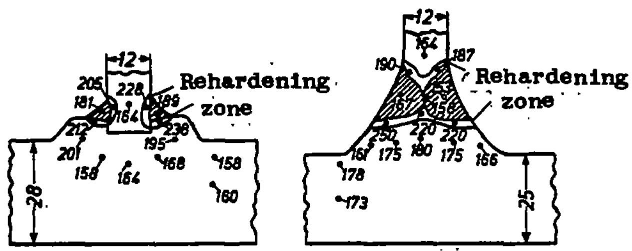


Figure 6.- Frequency curve of the temperature at crack formation in chrome-molybdenum steel sheets according to A. Antonioli.

Figure 7.



Front cross section. Elevation cross section.

Figure 8.- Rehardening in welding of a front cross section and a reinforced elevation cross section of St 52 (according to R. Kühnel).

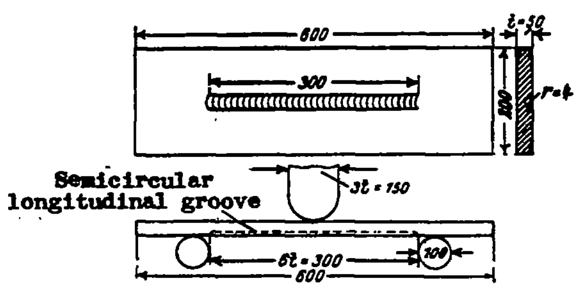
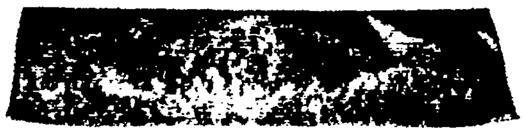


Figure 9.- Dimensions of the free-bend test specimen.

Deformation fracture.



Mixed fracture.

Rupturing fracture.

Figure 10.- Various types of fracture in the free-bend test on 50 mm thick structural steel St 52 (according to H. Buchholtz).

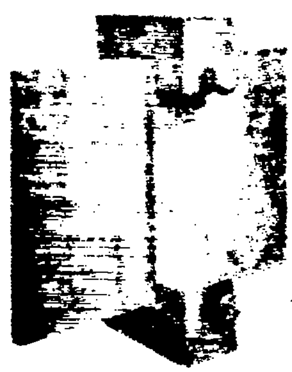


Figure 11.- Clamp welding test according to T. Wilkinson and H. O'Neill (LMS-test).

Visibleness of the cracks	Grade
Free from cracks	1
Only when magnetically tested	2
Only when polished with emery paper	3
After filing	4
After sawing	5

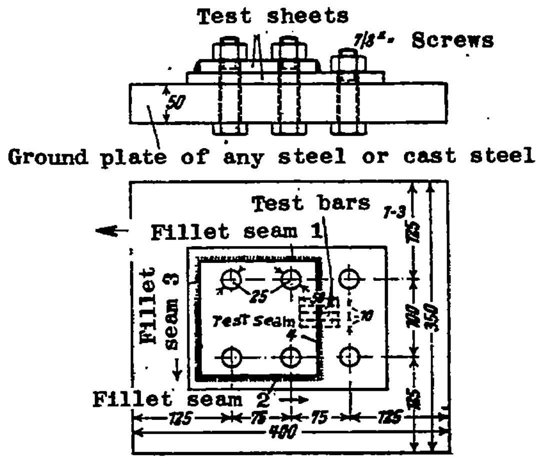


Figure 12.

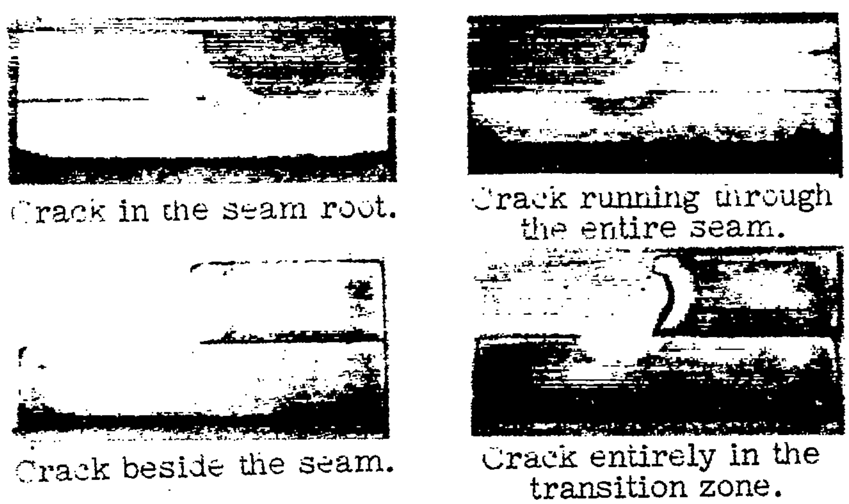


Figure 13.- Various types of appearance of cracks in Swinden-Reeve test specimens (etched).

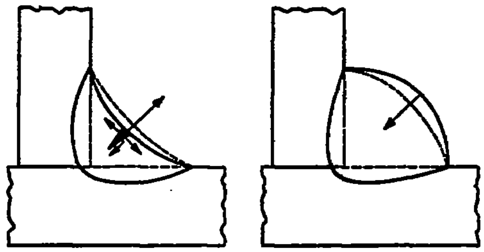


Figure 14.- Schematic representation of the influence of the form of the seam on the stresses appearing in the fillet seams (according to C. Stieler).

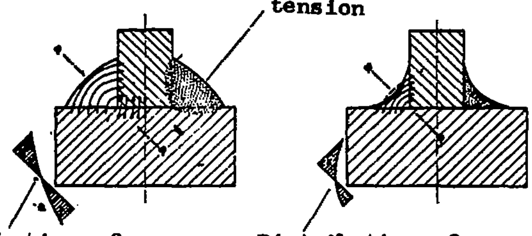


Figure 15.- Shrinkage in fillet seams according to G. Bierett.

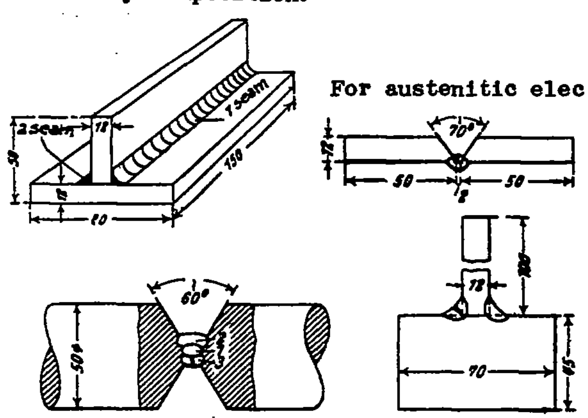


Figure 16.- Methods for testing the susceptibility to welding seam cracking (according to Stieler).